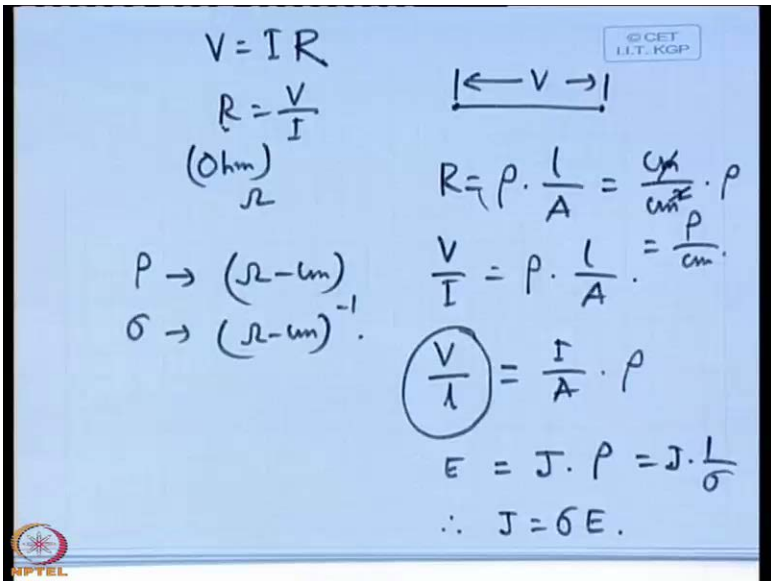
Processing of Semiconducting Materials
Prof. Pallab Banerji
Department of Material science
Indian Institute of Technology, Kharagpur

Lecture - 2
Electrical Conductivity of Materials

(Refer Slide Time: 00:43)



Electrical conductivity of materials, right. In electrical conductivity of materials first thing what I would like to introduce is the concept of resistivity. What is the difference between resistance and resistivity? Resistance you all know comes from the ohms law, V equals to…

Student: I R.

I R. If you have a current running conductor, the potential difference between 2 ends is a V, and I amount of current passes through it, then we can write using ohms law V equals to I R or R equals to V by I, but this is resistance, it is unit is ohm.

Student: Ohm.

It is unit is ohm, but then why it is required to familiarize with the resistivity, who can tell?

Student: It is the property of material (( )) specific property of materials.

Right, very good.

Student: Thank you sir.

Basically the resistance is the material dependent, shape dependent characteristic - shape dependent, if you have different types of shapes. Because the resistance will be different, but for resistivity it is the intrinsic property of the material which is fixed for a material. Let me discuss this thing R equals to V by I, another thing you know that R equals to rho into l by A, that you know.

Student: Yes.

What is this?

Student: Resistance, resistivity.

Which one, rho.

Student: Rho.

L is…

Student: Length.

And A is the area of cross section of the…

Student: (( )) conductor.

Material of the conductor right R equals to rho into l by A. Now, let us have some small mathematics R equals to rho into l by A, and R equals to V by I. So, if you put V by I here, V by I equals to rho into l by A, V by I equals to rho into l by A. Here let us have this kind of a structure that V by l equals to I by A into rho can I write.

Student: Yes sir.

V by l equals to I by A into rho, what is V by l?

Student: Electric field.

It is electric field, it is E equals to what is I by A?

Student: Current density.

Yes, it is denoted by J current per unit area, if the current is in ampere and area is in say centimeter square then ampere per centimeter square is the unit for...

Student: Current density.

J or the current density, and it is rho.

Student: Resistivity.

Rho is basically 1 by sigma the conductivity.

Student: (( ))

Rho is equals to 1 by sigma the conductivity, therefore J equals to...

Student: Sigma E.

Sigma E. So, this J equals to sigma E is another form of ohms law, this is another forms of ohms law which is not material dependent. This conductivity sigma or the resistivity rho is the intensive property of the material, and its unit is ohm centimeter for resistivity; resistivity unit, what is the unit resistivity? Ohm centimeter, you can calculate from these relations you can calculate from this relation R equals to rho into l by A.

Student: Rho.

So, what is rho? Rho is ohm centimeter basically, because length you see that length is in...

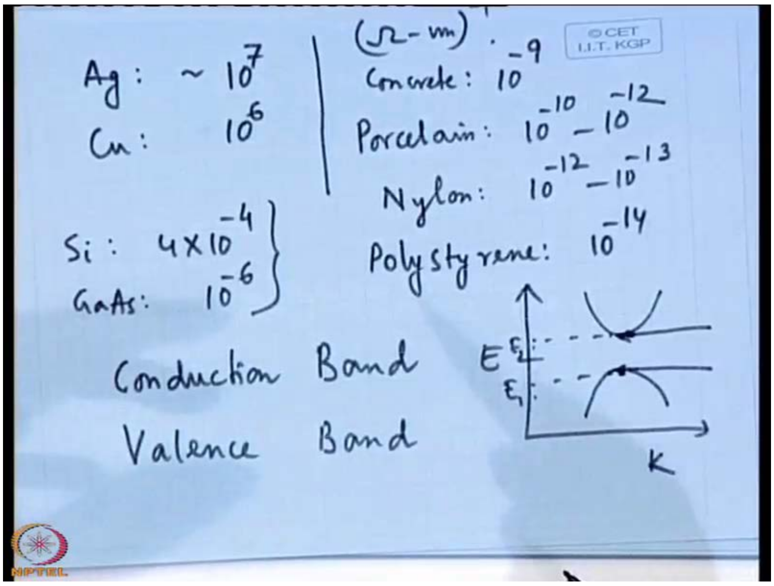
Student: Centimeter.

Centimeter, and area is in centimeter square and rho. So, centimeter rho by centimeter, R equals to rho by centimeter or rho equals to R centimeter; that means ohm centimeter. So, resistivity is ohm centimeter and obviously the conductivity will be ohm centimeter inverse..

Student: Inverse.

1 by rho or 1 by ohm centimeter. Now, let us have some conductivity electrical conductivity of some materials, let us discuss about the electrical conductivity of some materials. Let us start from metal.

(Refer Slide Time: 05:27)



Let us start from metal. What is the electrical conductivity of say silver, what it is value?

Student: 10 into the power 7.

Yes, say around 6 or 7 into 10 to the power of 7 of the order of 10 to the power 7 then it is...

Student: Copper.

Copper, how much?

Student: 10 to the power 4.

10 to the power of 4 or 6

Student: 10 to the power.

6.

Student: 6.

Gold 4.

Student: Gold 10 to the power of 4.

Yes. Then aluminum 10 to the power 4. So, those values are they are for the…

Student: Conductors.

Conductivity of this metal another set of metal say ceramics metal say concrete, what is the value 10 to the power…

Student: Minus 9.

Minus 9.

Student: Minus 9.

Concrete is a minus 9, porcelain.

Student: (( ))

10 to the power minus 10 to 10 to the power minus.

Student: 12.

12 right, say nylon 10 to the power minus 12 10 to the power minus 13, then polystyrene it is 10 to the power minus 14, all in ohm meter inverse unit remember.

So, what we see that that the metals are very conducting. So, far as the electrical conduction is concerned and this concrete porcelain nylon polystyrene etcetera, those are basically insulator in nature, because the conductivity is very, very less; it is almost there is no conductivity in it. So, those are insulator 10 to the power minus 12, 10 to the power minus 14; it is almost there is no current that can be conducted through those material.

Let us take another example of silicon, it is 4 into 10 to the power minus.

Student: 4.

4. Then gallium arsenide it is 10 to the power minus 6 right, these are known as semiconductor, whose conductivity basically lies between that of metal.

Student: And insulator.

And insulator.

So, now in terms of band diagram, in terms of band diagram if I would like to explain the metal, semiconductor, and insulator, then how I can explain. What is the difference in band gap between the metal, and a semiconductor and an insulator.

Similarity is metallic in nature.

But what is in between?

Student: (( ))

What is in between? What is there above in between and below in between? Also band gap for conductivity.

No, band structure because I have to explain these result one the basis of the band diagram in materials, because ultimately what is the origin of such kind of value, the metal conducts very early and much more than semiconductor or the insulator.

Student: Availability of electron.

Yes, but availability of electron, but from where the electron will come?

Student: From the movement of electron from one band to another (( )).

Right, so that means that means what you are telling basically there are two bands.

Student: Yes sir.

One is known as valence band another is known as the…

Student: Conduction.

Conduction band as the name implies conduction band basically determines the conductivity all kinds of electrical conduction will take place in the conduction band. So, unless there is electron in the conduction band, the material cannot be used as a conductor. So, the precondition is that you must have free electrons in the conduction band. You must have free electrons in the conduction band to have a conductivity of the material, but from where that free electrons will go to the conduction band, because the general idea is that the conduction band is empty, and the valence band is full why because…

All the electric energy...

From where the electron will come.

Student: Outermost energy (( )) valence band.

Yes from the valence band basically, outermost orbit means…

Student: Balance band.

Balance band right. So, from the valence band the electrons will come to the conduction band. So, the origin of electron is in the valence band, that is why we tell that the valence band is full at 0 k, and the conduction band is empty. And you need some force some electrical mechanism or say some excitation be it electrical optical or anything heat. So, that some of the electrons…

Jumps from the... Jumps from the valence band to the…

Student: Conduction band.

Conduction band to have some free electron in the conduction band which will give you the conductivity of the material. So, in terms of band diagram, I can tell that basically there are two bands; one is known as the conduction band, another is the valence band; generally the bands are parabolic in nature - generally the bands are parabolic in nature, and if you plot the band in E k diagram, what is E k diagram? E k diagram is…Energy verses propagation inverse. Along y axis. Energy. Energy, along x axis.

Student: Propagation inverse.

Propagation vector k which is nothing but the momentum, I shall show you how k and p is related. P, we discussed. Yes. So, basically if you tell that it is a propagation constant or wave vector. So, the general idea is that it is momentum, because for physics students it is very easy to conceive the idea of that h cross p k etcetera, but for other students momentum is very easier to understand. So that means, in the x axis it is basically the momentum or the energy wave vector, the wave vector or the propagation vector in the x axis it is the energy and the bands will look like this, it is basically the parabolic in nature. You see that there is a... Bottom.

Student: Bottom or the minima of this band.

Yes.

That is known as the conduction band minima; that is known as the conduction band minima. Similarly, there is a top point or a maximum point for the valence band, that is known as the valence band.

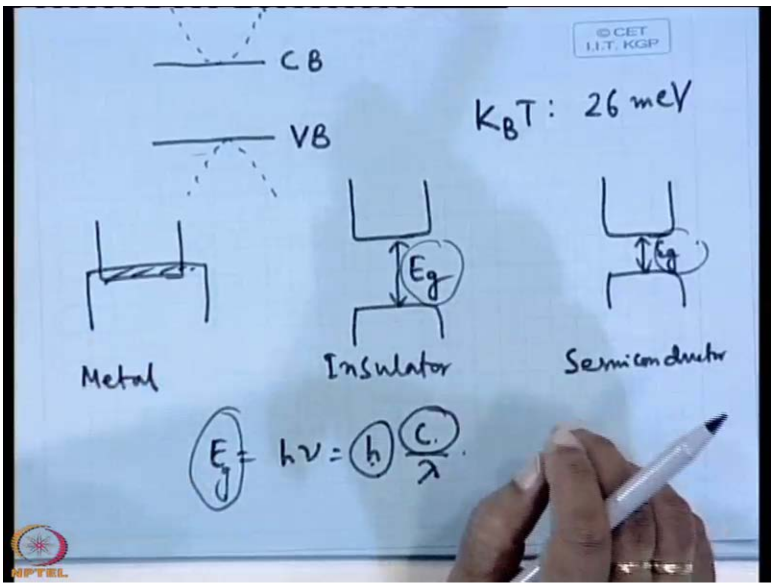
Student: Maxima.

Maxima. And the distance between the top of the valence band and the bottom of the conduction band is known as the band gap of the material. So, band gap of the material is nothing but the energy distance measured in energy, the distance which is measured in the unit of energy, here you see that it is.

Student: Electron, closing gap.

Yes, say say it is E 1 and it is E 2. So, difference between E 2 and E 1 is the band gap E 2 minus E 1 right. So, band gap means the energy difference between the top of the valence band and the bottom of the conduction band.

(Refer Slide Time: 14:25)



So, when we draw two lines to denote the band gap; this is CB, it is VB; CB is the conduction band, VB is the valence band that straight line basically the top and the bottom positions that basically the top and the bottom positions. So, generally we use two straight lines, parallel to straight lines parallel lines to denote the band 2 bands. So, this line that is the bottom of the conduction band, and that is the top of the valence band yes.

Student: Using of this conduction band parabolic, sir why these are parabolic in nature?

Why these are parabolic in nature then we have to solve the Schrodinger wave equation and other types of formalities. So...

Student: Sir.

So, I am not going into details all such things.

So, basically this type of band, and this is the band. So, these two bands are involved in conduction process for semiconductor for metal what happens? The bands... Bottom (( )).

Student: Overlap.

Yes.

The bands overlap generally in the valence band there, there is full of electrons and conduction band it is empty, but for metal for metal say this is the conduction band and that is the valence band. So, in some portion the band overlaps, some portion the band overlaps. What is the implication of overlapping? The implication of overlapping is that already there are some free electrons in the conduction band, because you cannot separate they are overlapped, they have touched right.

So, since there is a overlapping. So, already there are some free electrons in the conduction band, that is why metal conductivity is very, very high; already there are electrons to conduct current in the material, right. Then for insulator, this is the band gap E g, E suffix g and you see that the gap is wide, the gap is wide you can tell me sir sir how wide it is? It may be 3 electron volt, 4 electron volt, 5 electron volt, 7 electron volt, 8 electron volt. I cannot say any cut off value, I cannot say any cut off value because there are several wide band gap semiconductors which have very high band gap, even then they are known as the semiconductor. There are some ceramic material particularly electro ceramics whose band gap is small, even then they are regarded as the ceramic material.

So, that is why I shall not go into any cut off value, that what should be the cut off for semiconductor? What should be the cut off for the insulator? But it is several electron volts. Several electron volts mean it may be 4, 5, 6, 7, 8, 10 electron volt. And for semiconductor this value is less, this value is small then what is the implication of such a small value? The implication of such a small value is that even at room temperature. What is the thermal energy at room temperature, what is the thermal energy at room temperature? It is k t, it is k t.

What is k? It is Boltzmann constant what is it is value? 1.3 10 to the power minus 23 and what is the value of t at room temperature 300 k. So, if you multiply 1.38 into 10 to the power minus 38 multiplied by 300 electron volt.

Student: 1.54.

No, what is the room to my (( )) is 26 milli electron volt, it is 26 milli electron volt the thermal energy at room temperature is 26 milli electron volt 25.9 is precisely. So, at a room temperature this value is always the, that is known as the thermal energy. So, when the band gap is small, the valence band electrons can gain energy from the thermal source, and they become energized they jump from the valence band to the conduction band. So, that at normal room temperature in semiconductor materials always there is some free electrons.

Free electrons in the conduction band. So, the idea is that the gap is so small, because we have seen that what is that gap in germanium? It is 0.67 electron volt, 0.67 electron volt is very small value, even for narrow band gap materials indium antimonite, gallium antimonite it is even less 0.18, 0.19, 0.17 electron volt right. So, the value is very small.

So, that at normal room temperature, the electrons in the valence band will gain energy from the thermal source, and they will jump from the valence band to the conduction band. So, that you will get some free electrons in the conduction band even at room temperature, that is why those materials are known as semiconductor. In conductor they are overlapped, in semiconductor they are not overlapped; in semiconductor they are not overlapped, but at normal room temperature because of the thermal energy you will have some energy in the conduction band which will give rise to conductivity of the material, that is why they are known as the semiconductor. Remember that at 0 k at absolute 0 temperature a semiconductor will act as a... Insulator (( )).

Insulator. A semiconductor will act as an insulator you will not get any free electron in it right, but in case of insulator the gap is so high that even at normal thermal energy, no electrons will move from valence band to conduction band, because say the difference is 4 electron volt or 6 electron volt; 4 electron volt and 6 electron volt is very high energy, so far as an electron is concerned right. And so at normal room temperature you will not get any free electron in the conduction band of the insulator, that is why they are insulator. So, the idea is that you have some 3 electrons in the conduction band of the material to get some conductivity out of it unless there is free electrons you cannot.

So, this is the difference between the metal insulator and semiconductor, so far as the band diagram is concerned remember that these are the basically free hand sketch of the band diagram, it is the parabolic in nature, but we can use this straight line or that type of a block to put put forward our idea right .

Now, another thing is that the relation, which I have shown you earlier that 1 lambda equals to 1. 24 by E g can you remember that value yes, that thing it is 1.24 by E g from where this relation comes. No, from where this relation comes how can I say that lambda equals to 1.24 by E g, is it god gifted no, then…

Student: (( ))

Yes, exactly exactly E equals to h nu; nu equals to C by lambda, this C is the velocity of light its value is 3 into…

Student: 10 to the power.

10 to the power.

Student: 8 meter per second.

8 meter per.

Student: Seconds.

Second then h is planck’s constant whose value is...

Student: 6 point 6 (( )) joule second.

Joule second and lambda is your...

Student: Wave length.

Wave length, this lambda.

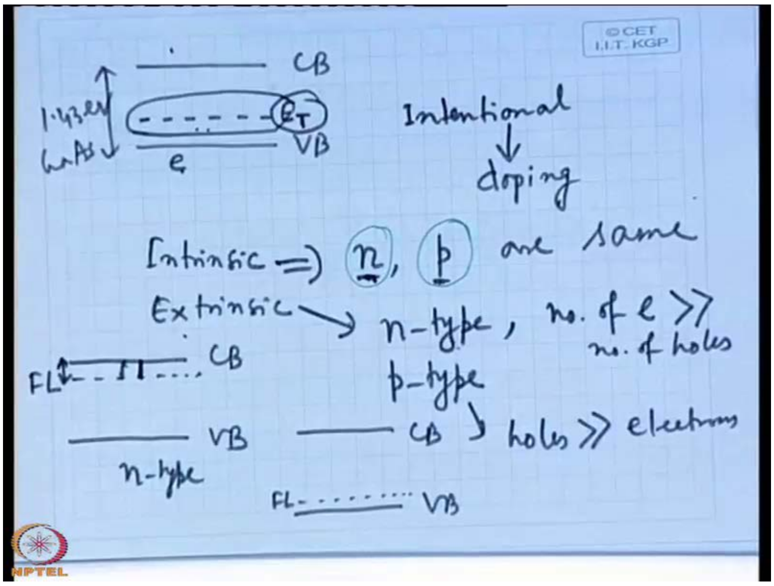
Student: (( ))

And if you put the value of h and see and simplify, and then this use this unit electron volt and micron then you will get lambda equals to 1 point 2 4 by E g. If you do not take it micron, then there will be additional terms 10 to the power something. If you do not use electron volt and use joule, then there will be a difference of 1.6 into 10 to the power minus.

Student: 19.

19 right. So, the conversion of unit is very important in this case, and this relation comes from E equals to h C by lambda, and if you put h and see then you will get this value. Now, this is the band gap E g. So, if this is your band gap, so how much energy is required to excite 1 electron from the valence band to the conduction band E g, the minimum amount of energy is E g very good minimum amount of energy is E g you need at least E g, you need at least E g. So, let us take another example of say gallium arsenide.

(Refer Slide Time: 26:10)



Say this is the conduction band, and this is valence band and the value is 1.43 electron volt.

Student: Sir.

Yes.

Student: What is in between the conduction band and valence band?

Yeah, very good question, very good question he has asked me what is there in the band gap, is there anything, no. Ideally there is nothing in the band gap that is why it is known as the forbidden gap, ideally there is nothing in the band gap it is forbidden gap ideally remember ideally.

Student: Means an electron can upstart between those.

No ideally it is not possible. But in real crystal when we talk about a semiconductor or a ceramic or some material or say polymer, because one important application of polymer is in electronic device you know that the organic semiconductor devices. Though those are polymer materials, but their conductivity is even comparable to the metal in some cases fantastic large conductivity. And people have exploited those huge value of the conductivity to use them in electronic device particularly in light emitting diode patch panel display, then auto voltaic device that is solar cell already it is there.

So, for large area device, so I shall discuss those things in detail in some later classes. So, what is there in the band gap ideally there is nothing; but any crystal whatever precaution you take you cannot avoid impurity in it, you cannot avoid impurity in it right. Say if you want to make a silicon crystal we shall discuss those things, if we want to make a silicon crystal what is the starting material? The starting material is a sand, the starting material is the sand that is why it is cheap and inexpensive, but there is some chemical treatment for its purification. After purification there is a process known as the crystal growth process - bulk crystal there is epitaxial crystal also that is a separate issue. So, first a material is purified and the crystal is grown by some methods of crystal growth

If you take a sample of that crystal, whatever precaution you have take you take there may be some impurity in it. And that impurity will have it is energy level in between the bottom of the conduction band, and top of the valence band. That means, in the band gap. So, in the band gap there can be electronic level in the band gap there can be electronic level.

Student: Level electronics can stop.

That is a separate story, electron is very choosy - electron is very choosy unless it has some specific room for it, it will not move.

Student: (( )) non radiation process.

No, no forget about the radiative non radiative type of thing, electron for the destination suppose you a electron will jump from valence band to conduction band. In the conduction band there must have a level for it, if all the levels are full then it will not move it will not move, and also you know that because of the spin plus half and minus half in one level how many electrons can stay two. So, if suppose this is a material in it is band gap it is say there is no electronic level in the conduction band there are only two levels theoretical consideration how many electrons can move.

Student: Only less than 4 electrons.

Yes at the most 4 electrons can move from valence band to conduction band, how many electrons are there in the valence band. It can be 10 to the power of 17, 10 to the power

18, 10 to the power 19, 10 to the power 23. So, only 4 electrons will be able to move to the conduction band. So, that is why I tell that electrons are very choosy.

Student: Sir, one more question there is the top of valence band (( )) 10 electron volts.

Top of the valence band.

Student: (( )) electron.

How? Is the gap is 10 electron volt.

Student: Yeah between the of this valence band.

No, no the band gap is 10 electron volts or what you are talking about.

There the energy level, where the valence band lies…No, no even valence band lies means that is the difference when you talk about the band gap, it is the difference in energy, it is a difference in an energy.

Student: Before the band gap is 10 electron volts.

Yes. And we supply the energy of 5 electron volts.

Yes, that I am telling suppose the band gap is 10 electron volt and you are would like to supply 5 electron volt of energy then nothing will happen. The electron will not move because for the movement of electron at least actually I had started there thing. See 1.43 electron volt is the band gap of the gallium arsenide, 1.43 electron volt. Now for sending an electron from valence band to conduction band at least 1.43 electron volt energy is required. So, if the energy is less than 1.43, no electron will move no electron will move ideally, but if there is an electron level in the forbidden gap. There is an electron level in the forbidden gap which I have shown you using a dotted line with a broken line that is known as E t, what is that?

Student: (( )) fermi electric.

No not fermi electric, that is basically a defect level, that is basically the defect level t tends for trap TRAP trap level, why trap level? Because...

Student: (( )) energy level of electron.

No, no because it can trap an electron.

Student: (( )) can bond itself there.

Yes. So, if the energy is less than 1.43, but you have provided sufficient energy to reach to E t then 1 electron or the electrons can move from the valence band to E t level or the trap level that is all, but provided that is the level there. So, ideally there is nothing in the band gap it is completely forbidden gap, but due to the fabrication or processing of materials unintentionally there can be level in the material in the band gap which can act as the defect level. So, in the band gap you can find other levels as well.

So, when I talk about levels it is basically the energy level, it is basically the energy level a part of the E k diagram. If there is a level then electron can reach there if there is no level electron will not move. Another consideration is that this level in the band gap can be intentional or unintentional can be intentional or unintentional, in intentional case basically if you dope a semiconductor. Intentional means intentional means doping; intentional means doping of the material- if you dope the material then the material can be converted into p type or n type remember, the material can be converted into p type or n type material.

So, intentionally you have added impurity in it right, intentionally you have added impurity in it that is the case for dope semiconductor; semiconductor can be broadly classified into two category. One is intrinsic, another is extrinsic; one is intrinsic, another is extrinsic. Intrinsic means where you have not doped the material; in intrinsic material the number of electrons and holes are same the number of electrons and holes are same. At this point I must tell you the difference in conductivity V 2 in a metal and a semiconductor, in metal the current is carried by the electrons only in semiconductor. The current is carried by both the electrons and the holes, so that a difference remember.

In semiconductor the conductivity is basically bipolar in nature, both the electrons and the holes take part in the conductivity, but in metal only electrons take part in the conductivity right. So, metal cannot be considered as intrinsic or extrinsic, but semiconductor it can be intrinsic where the number of electrons and holes are same when I talk about n, n is means the number of electrons n negative, electrons are negative that is why n stands for the electrons, p are positive basically p stands for positive and p is the holes, because holes and electrons are differed by their charge. Absence of electron means.

Student: Holes.

Holes created, say in this case by some means you have excited 1 electron and it have jumped from this valence band to...

Student: Conduction band.

Conduction band from valence band to conduction band. So, this electron which is jumped to the conduction band, what will be there here in valence band.

Student: There will be a hole.

There will be a hole, then the electron it moves from this place to that place another hole will be created here. So, the conduction mechanism is in that manner that the electron moves if the electron moves from left to right the holes moves from…

Student: Right to left.

To left right. So, in semiconductor the intrinsic the electrons and holes take part in the conductivity, and in intrinsic semiconductor the number of holes equal to the number of electrons right, but in extrinsic semiconductor - the extrinsic semiconductor is processed by doping. Intentionally you would like to increase the number of holes or electrons in the materials intentionally or some reason you have you would like to do it say.

So, in extrinsic semiconductor can be n type or can be p type, it can be n type or it can be p type, for n type the number of electrons is very, very greater than number of holes; for p type number of holes are very, very greater than number of electrons. So that means, for making an n type semiconductor, you have no other way, but to dope it right. So, when you make some doping on a semiconductor it becomes extrinsic, and in that case the number of electrons and number of holes are not equal. The number of electrons and number of holes are not equal they differ in number.

So, do not say that intrinsic semiconductor are the pure semiconductor not that all semi conductors are pure semiconductors, it is not between purity and impurity. It is between the number of electrons and holes, if they are equal it is intrinsic if it is different they are extrinsic. And that can be done intentionally or unintentionally when there is an impurity suppose we have grown 1 silicon crystal and iron is there or magnesium or sodium is there in the silicon crystal. So that means it is impurity, intentionally you have not done it, unintentionally during process of growth it is there. So, it will give rise to this additional line otherwise if it is an n type semiconductor then for n type semiconductor there will be a fermi level that fermi level will be just below the conduction band, it is fermi level just below the conduction band. And for p type it is just above the valence band.

Student: Sir, why we introduced fermi level.

Why we?

Student: Introduced formula.

Yes we introduce fermi level means up to that level you will find some electrons up to that level you will find some.

Student: By means of excitation.

Yes, by means of excitation or without any excitation. So that means, when there is an n type semiconductor; that means only this much of energy you have to supply only this much of energy, only this much of energy we have to supply. So, that the electrons can move from the fermi level to the conduction band, basically this is the donor level; basically that is the donor level up to that point electrons available. So, small energy is required for excitation of the electrons from that point to the conduction band. So, that is the physical implication of fermi level, you can do a lot of mathematics, so far as the fermi level is concerned, but that is not required in our case. So, very small amount of energy is required to excite an electron from this point to that point.

Student: Excuse me sir.

Yes.

Student: Sir, electrons which is a jump from fermi level to conduction band.

Yes.

Student: That electron will be of a doped atoms or...

Which one.

Student: The electron which jump from fermi level to conduction band.

Yes, that electrons of doped atoms or...

Yes, obviously if there is n type semiconductor. So, already there is some electron n type means that thing only, you have intentionally doped because of that reason only. Otherwise why you will dope the semiconductor with some machine either diffusion is required or ion implantation is required, because for diffusion or ion implantation you need some technology you need some money. So, if you say that there is electron excess of electrons is required in a material, particularly in semiconductor you have to reserve to doping and n type doping is required if you need some electrons in it, because you have injected electron in it. What is the implication of doping?

Let us be very clear in it, the implication of doping is that you have to have many electrons in the material, suppose this is the material and you need some electrons in it from where the electrons will come it will come from doping only, it will come from.

Student: Doping.

Doping only let us take the example of silicon.

Student: Sir, time (( )).

One minute, let us say one thing that say there is silicon 1 minute just silicon. So, in silicon you see that it is a group 4 element. So, 4 electrons are there in it in the outermost cell, if you dope with phosphorous; phosphorous belongs to group 5 of the periodic table. So, out of those 5 electrons 4 electrons will form covalent bond with this four.

Student: Silicon electron.

Silicon electrons right, they will share among themselves, and only one electron will be unpaired. So, that electron will be free very easily you can detach it from the atom. So, that is the free electron. So, if you dope say 10 to the power 2 A of 10 to the power 14 number of silicon with 10 to the 14 number of phosphorous then you will get 10 to the power 14, 10 to the power 15 number of electrons. So, that is why you dope otherwise why you will dope.

Student: Sir with that number of free electrons can move in valence band.

No, no they they are ready to jump to the conduction band, if you supply that amount of energy.

Student: (( ))

Yes. So, the how much energy can be supplied that I shall discuss in my next class. So, let us conclude this session by saying that the conductivity of the metal semiconductor and insulator basically related to the band structure of it in metal we have seen that they have overlapped in insulator the gap is very high. So, at normal room temperature, it is not possible to excite the electrons from the valence band to the conduction band, but in case of semiconductor normal room temperature some electrons can jump from the valence band to the conduction band, because of the thermal energy associated at the room temperature or from other normal sources. So, that you can have electrons in the conduction band which gives rise to the conductivity, and another thing is the conductivity is an intrinsic property of the material which we have said.

Thank you.